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LAV ARMOR PLATE STUDY

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ABSTRACT

This study was undertaken to determine the cause of cracking in high hard armor steel plates used in the manufacture of light armored vehicles (LAVs) and to make recommendations to alleviate the problem. Cracks in several components from fielded vehicles were analyzed. In many cases the cracking was found to be caused by improper edge preparation in cutting the steel which resulted in environmentally-assisted cracking. Cracks were also observed starting from welds which were attributed to a number of possible causes: stress-corrosion cracking, hydrogen-assisted cold cracking, and cracking due to extremely harsh vehicle use. Base metal mechanical properties, including hardness, tensile strength, and Charpy V-notch impact energy were measured from room temperature to -40°F (-40°C). Ballistic properties were measured and the propensity of the steel to crack under ballistic impact conditions was also evaluated. Additionally, the study involved a review of MIL-A-46100 and the new Canadian Material Specification, CMS-18.

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INTRODUCTION

The original mission was to address concerns of the suitability of MIL-A-46100 High Hardness Steel Armor in the structural application of the light armored vehicle (LAV).[1]

The family of LAVs made for the U.S. Marine Corps (USMC) were fabricated from light gage (4.71 mm to 9.71 mm nominal thickness) high hardness steel armor (MIL-A-46100) above the beltline. This was one of the first uses of high hard armor in a welded structural application. High hardness steel armor is tempered at low temperatures, below the temper embrittlement range and in the first stage of tempering, and the resulting strengthening dispersion consists of epsilon carbide. The steel was chosen to maximize ballistic protection against the defined threat (7.62-mm M1943 ball, AK47 round) while maintaining vehicle lightness. Other authors had strongly recommended against continued use of this steel because of its purported brittleness. Many vehicles had exhibited cracks of varying severity in the steel plate. However, the U.S. Army Materials Technology Laboratory (MTL) approached the problem from a different viewpoint.

Since vehicle production of this series had been completed, the object of the study was to determine the cause of cracking, to examine weld repair procedures and to recommend steel compositions and manufacturing procedures to minimize cracking in the present and future vehicles. An examination of failed components was made, mechanical and ballistic properties of representative plates measured, and other available information reviewed.

MATERIALS AND TESTING PROCEDURES

Failed Components

Several parts of fielded LAVs containing cracks were received for analysis. Most of these failures had occurred much earlier and the crack surfaces were quite rusted. However, based upon the pieces examined and previous studies, the failure mechanisms are thought to be similar; therefore, this report details cracks in a hatch cover and a rear door.

Plate cutting and grinding procedures used during vehicle manufacture are thought to play an important role in determining vehicle integrity. Plate samples cut by plasma-arc in air, plasma-arc under water, oxyacetylene, carbon-arc in air, dry abrasive cutting wheel, and laser were obtained for examination. These samples were then sectioned for metallographic examination and microhardness traverses.

When this study was initiated, a vehicle lifting restriction was in place. No lifting was permitted at ambient temperatures below 32°F (0°C). Two LAVs had been dropped from helicopters and the cause was not immediately apparent, although subsequently it was determined that both vehicles were dropped intentionally because of helicopter malfunctions. The following phrase in MIL-A-46100B and C under Paragraph 6.1 (Intended Use) was also of concern:

> "The steel armor covered by this specification is intended for structural use in lightweight applications generally up to and including 1-1/2 inches in thickness, operating at temperatures in excess of 32°F, where resistance to ball and armor piercing types of ammunition and multihit capability are required."

1. KRENZKE, M. A. *LAV Cracking Problem Investigation and Analysis Study Estimate.* Memorandum. Department of the Navy, David Taylor Research Center, Annapolis, MD, 13 January 1989.

In a separate but closely related study,[2] several mock-up lift-eye structures of the right front eye were tested at room temperature and at -25°F (-32°C). In addition, actual vehicle lift tests were conducted at the same two temperatures. Details of the testing are given in an MTL Letter Report.[2] The MTL test results closely agreed with previous data from General Motors and as a result the lifting restriction was removed.

For completeness, some details of the lift-eye structure are given below. The LAV lift-eye is fabricated from ASTM A 514, Grade S, steel of the following composition (wt%):

C	Mn	Si	P	S	Mo	B
0.17	1.38	0.32	0.005	0.009	0.28	0.0010

The eyes, about 1" x 1-1/4" in cross section, are welded to the vehicle side panels (7.31 mm thickness). A view of one of the eyes is shown in Figure 1a, and a cross section of the weld in Figure 1b. The three-pass weld can clearly be seen; it consists of an initial root pass followed by a second pass along the high hard armor plate, and finally a third pass against the eye.

Materials

For this study, four steel plates of MIL-A-46100 high hardness armor steel were ordered from the Diesel Division of General Motors (DDGM). These plates are typical of material for LAV production and were made by the Lukens Steel Company to MIL-A-46100C (Revision C). The chemical analysis of these plates is given in Table 1.

Table 1. CHEMICAL ANALYSIS OF MATERIAL USED IN THIS STUDY

Composition (wt%)	6.31 mm (1/4 in.)	7.31 mm (9/32 in.)	7.31 mm (Extra Hard)	9.71 mm (3/8 in.)
C	0.29	0.31	0.31	0.31
Mn	0.83	0.87	0.87	0.96
Ni	0.90	1.16	1.16	1.10
Cr	0.47	0.54	0.54	0.52
Mo	0.53	0.55	0.55	0.55
Si	0.38	0.43	0.43	0.39
Al	0.030	0.036	0.036	0.025
P	0.015	0.010	0.010	0.015
S	0.001	0.002	0.002	0.003
HRC	48	50	51	48
Plate Dimensions (in.)	65 x 165	65 x 220	65 x 220	72 x 100

NOTE: The heat treatment was as follows:

Austenitizing	1660°F (904°C)	~ 20 min
Spray Water (Roller Quench)		
Tempering	400°F (204°C)	~ 50 min for 3 plates 30 min for the extra hard (XH) plate

2. BETHONEY, W. M., and CRENSHAW, W. L. *Light Armored Vehicle (LAV) Lift Hook Test.* U.S. Army Materials Technology Laboratory, Letter Report, September, 1989.

Hardness and microhardness measurements were made both on the plate surface and on polished cross sections. Tensile and Charpy V-notch impact measurements were made in the longitudinal and transverse directions. The tensile specimens were flat, 3/16 in. thick with a 2 in. gage section. The Charpy specimens were all half size because of the original plate thickness. Equal amounts of material were removed from both surfaces in the preparation of these mechanical test samples.

Ballistic Testing

The LAV is principally designed to defeat a 7.62-mm M1943 ball threat (AK47, muzzle velocity 2380 ft/s). It would also be desirable to defeat other heavier threats such as 12.7-mm (.50 cal) API and even 14.5-mm projectiles. In the latter cases the design threat would be at lower velocities, i.e., greater stand-off distances, against armor at high obliquities. There was also a lack of data on MIL-A-46100 at low temperatures; therefore, it was decided to run a series of ballistic tests on the four plates described above. Three threats were chosen: 7.62-mm M1943 ball, 12.7-mm (.50 cal) API B32, and a 20 mm 70 g proof round. The blunt- (flat-) nosed proof round was used to determine the propensity of high hard steel armor plate to crack under ballistic shock loading conditions, particularly at low temperatures. The proof rounds were made from AISI 1018 plain carbon steel. A photograph of the three projectiles including dimensions is shown in Figure 2.

The V_{50} values were obtained according to the *Ballistic Protection Limit* criterion. A witness plate of 0.020 in. thick aluminum is placed behind the target and any penetration of the witness plate by either the projectile or parts of the projectile or target, i.e., back spalls, plugs, etc., is defined as a target penetration. The V_{50} velocity is then the average velocity of the three projectiles (sometimes two were used) with the highest velocities that do not penetrate the target and the three (or two) with the lowest velocities that penetrate the target. Projectile velocities are varied by and are dependent upon the amount of charge in the cartridge.

The measurements at a test temperature of -40°F were made by first pre-immersing the subject plate in a low temperature freezer overnight at a temperature significantly lower than the test temperature. When ready for testing, the plates were removed from the freezer and placed in the target rack. The plate temperature was continuously monitored with a thermocouple and when it reached -40°F one ballistic test (one shot) was made. The plate then went back into the freezer and the cycle continued until testing of the plate was completed.

RESULTS AND DISCUSSION

Analysis of Cracked Components and Plate Edges

Rear Door

Figure 3a shows a cracked door from an LAV-25. Microscopical examination for the edge of the plate at the crack origin revealed a layer of untempered martensite, as shown in Figure 3b. As discussed below, this layer results from the plate cutting operation and was not completely removed during subsequent grinding. This layer of untempered martensite is quite brittle and can be a crack initiation site. The Charpy V-notch impact energy of the plate in this door was measured in the longitudinal (LT) and transverse (TL) directions

(3/4 size specimens) from room temperature (72°F) to -40°F. No sharp transition temperature was observed (see Figure 4). The shape of the curve is typical for very high strength steels.[3]

Figure 5 depicts a typical cross section of the door showing the fine banding in the interior and the decarburization at the edge. Banding is present in all steels, to a greater or lesser degree, whether it is ingot or continuously cast. The banding results from local segregation (mainly of carbon) during the solidification process and, hence, will cause slight hardness variations. This example is shown to illustrate that care must be taken when evaluating microhardness traverses.

Turret Hatch Cover

A cracked turret hatch cover from a vehicle Model Number 25MC,DDGM S/N LAV 612, USMC S/N 521765 was received for evaluation. A copy of the field service report of the crack in this hatch is given in Figure 6. The crack length when the hatch was replaced on 15 July 1987 was 8 inches.[4] The crack has since grown to over 12 inches and may be seen starting at the weld at the rim and travelling into the center (see Figure 7a). During cut-out of the crack origin region, binding of the saw occurred and it was evident that considerable residual stress was being relieved. A macrograph of the rim weld and micrograph of the structure of the weld region are shown in Figures 7b and 7c, respectively. Again, there is a layer of martensite next to the weld metal. Typical microhardness traverses across a weld region are shown in Figure 8. This sample was taken from the weld between the right upper front quarter panel and the main front glacis from the LAV that was dropped at Camp LeJeune (now at MTL). As this is a two-pass weld, two traverses were performed: the first just below the front surface (first pass), and the second just below the back surface (second pass). Moving from the weld metal to the base plate, the wide variation in hardness is readily apparent. The weld nugget is quite soft; then, after the fusion zone, there is a layer of very hard fresh (as-quenched) martensite in the base metal heat-affected zone (HAZ) that resulted from re-austenization during welding. The base metal HAZ hardness then drops into the region that did not see a high enough temperature excursion to be re-austenitized and so instead became heavily tempered. Following that, the steel is progressively less tempered during the welding operation and the hardness rises asymptotically to that of the (unwelded) base plate.

The cracking observed initiating from free-cut plate edges was often very similar to that observed in previous studies.[5,6] It was concluded that much of the cracking occurring in LAVs from free-cut plate edges may be attributed to environmentally-assisted cracking. For this mechanism to operate, the following conditions are necessary:

- A notch or crack initiation site must be present, e.g., quench cracks,
- The plate (component) must be under tensile stress (either residual or applied in service),
- The component must be in a suitable environment, and
- The material must be in a condition susceptible to environmentally-assisted crack propagation, e.g., untempered or first-stage tempered martensite.

3. ROLFE, S. T., and BARSOM, J. M. *Fracture and Fatigue Control in Structures*. Prentice-Hall, Englewood Cliffs, NJ, 1977.
4. LAV-PMO. *LAV Crack Status Report*. TACOM, Detroit, MI, 2 December 1987.
5. HERMAN, W. A., and CAMPBELL, G. M. *Environmental Assisted Cracking in High Hardness Armor Steel*. U.S. Army Materials Technology Laboratory, MTL TR 85-28, September 1985.
6. PHILLIPS, R. H. et al. *Delayed Fracture of High Hardness Armour Steel*. Australian Department of Defence, DSTO, Materials Research Laboratory, Australia, Final Report on TTCP PTP-1 Study Assignment PTP-A-S1, December 1990.

In the case of the LAV the latter three conditions exist in service and little can be done to change these given conditions, therefore, the risk of crack starters must be reduced. In vehicle manufacture, individual plate pieces are cut to shape by an underwater plasma-arc process. This procedure produces a layer of very hard, brittle untempered martensite at the cut edge that must be removed as soon as possible after cutting. Alloy steels in this condition are susceptible to a phenomenon known as delayed cracking. Some LAV components examined at MTL exhibited residual untempered martensite at free-cut edges that had not been completely removed during grinding.

Cut Edges

Table 2 illustrates the effect of various methods of edge preparation on the thicknesses of untempered martensite and the heat-affected zone.

Table 2. THICKNESS OF UNTEMPERED MARTENSITE LAYER AND HAZ

Edge Preparation	Thickness of Untempered Martensite (in.)	Thickness of HAZ (in.)
Water Jet Cut	Not Detectable	Not Detectable
Abrasive Wheel Cut (Dry)	Not Detectable	0.1
Plasma-Arc Cut (Air, High Speed)	0.02	0.1
Plasma-Arc Cut (Water)	0.02	0.1
Air Carbon-Arc Cut (Multipass)	0.04	0.15
Oxyacetylene Cut	0.12	0.6
Laser Cut	0.005	0.02

It is obvious from this table that more edge material must be removed (and consequently more time spent on its removal) when, for example, oxyacetylene cutting is used instead of plasma-arc cutting. It should be noted that laser cutting produces by far the thinnest layer of untempered martensite and HAZ. The water jet process does not produce either since it is done cold, but is too slow to be used in production even when one considers the time saved by eliminating edge grinding.

Mechanical Properties

Hardness

Although hardness and Charpy impact toughness are the only mechanical properties required by MIL-A-46100, other properties with relation to service and ballistic performance are of importance. After grinding off the decarburized layer (usually about 0.004 in. thick), hardness readings were taken on the surfaces of the four plates using the Brinell and the Rockwell C Hardness tests. Multiple readings were taken and averaged; the results are shown in Table 3.

Table 3. HARDNESSES OF THE PLATES INVESTIGATED

Plate Thickness (Nominal, mm)	Plate Thickness (Actual, mm)	BHN	HRC
6.31	6.50	512	48
7.31	7.24	512	50
7.31 (XH)	7.52	512	51
9.71	9.50	512	48

All of the plates were within specification; however, these results confirm that only an approximate conversion can be made from one hardness scale to another. It is also noted that the plate that was designated "extra hard" (XH) had the same Brinell hardness but was slightly harder when measured on the Rockwell C scale.

Charpy Impact Toughness

The Charpy impact toughness was measured on the four plates in both the longitudinal and transverse directions over a test temperature range from -40°F to the room temperature of 72°F. The results are given in Figures 9a through 9d for the four plates tested. It should be noted that there is no abrupt change in toughness values at any point over this temperature range. The toughness decreases gradually from room temperature (72°F) to -40°F. The Charpy values exceeded the requirements of MIL-A-46100 for three of the plates, while the 9.71-mm thick material had values slightly lower than specified; i.e., longitudinal 10 ft-lbs measured versus 12 ft-lbs specified, and transverse 9.5 ft-lbs measured versus 10 ft-lbs specified.

Tensile Properties

The tensile properties of the same four plates were measured at the room temperature of 72°F (22°C), and at -40°F. Duplicate measurements were made in both the longitudinal and transverse directions with respect to the primary rolling direction. These plates were cross-rolled; there is very little difference in properties between the two directions. The room temperature results are given in Table 4.

As would be expected, the 7.31-mm XH plate has a slightly higher tensile strength. All of the plates have good tensile ductility as evidenced by the percent elongation and reduction of area values. At -40°F (see Table 5), the tensile and yield strengths are slightly higher and the ductility slightly lower. This trend of higher strengths at lower temperatures is characteristic of alloy steels and correlates with the somewhat lower Charpy impact energies measured at lower temperatures. Note that only transverse tests were made at this temperature.

Table 4. TENSILE PROPERTIES OF HIGH HARD ARMOR AT ROOM TEMPERATURE

Specimen	UTS (ksi)	0.2% YS (ksi)	Elon. (%)	RA (%)
6.31 mm LT	252.2	202.7	10.4	44.5
6.31 mm LT	251.6	208.6	10.2	42.6
6.31 mm TL	249.7	200.8	10.5	44.2
6.31 mm TL	244.5	201.1	10.1	43.2
7.31 mm LT	259.2	209.3	10.0	46.1
7.31 mm LT	253.4	205.6	11.0	45.2
7.31 mm TL	254.7	206.7	10.3	48.0
7.31 mm TL	251.1	207.6	9.4	43.1
7.31 mm XH LT	265.8	207.0	9.8	41.5
7.31 mm XH LT	263.7	208.9	10.0	42.1
7.31 mm XH TL	266.4	209.5	11.3	36.1
7.31 mm XH TL	263.2	207.2	9.2	39.7
9.71 mm LT	250.0	197.7	12.0	48.8
9.71 mm LT	248.2	198.1	10.1	41.7
9.71 mm TL	249.7	204.1	9.0	48.4
9.71 mm TL	255.0	205.3	10.5	33.6

NOTE: LT = Longitudinal
TL = Transverse

Table 5. TENSILE PROPERTIES OF HIGH HARD ARMOR AT -40°F

Specimen	UTS (ksi)	0.2% YS (ksi)	Elon. (%)	RA (%)
6.31 mm TL	235.7	193.3	9.1	54.2
6.31 mm TL	255.0	209.9	11.2	50.1
7.31 mm TL	257.7	210.3	9.7	51.5
7.31 mm TL	258.5	209.4	9.7	51.2
7.31 mm XH TL	266.5	205.8	9.4	48.3
7.31 mm XH TL	266.0	205.3	10.2	47.9
9.71 mm TL	263.6	213.0	9.9	43.9
9.71 mm TL	263.0	219.1	9.7	47.1

NOTE: TL = Transverse

Ballistic Properties

7.62-mm M1943 Ball

The V_{50} value was obtained at 0^o obliquity at both room temperature (72^oC, 22^oC) and at -40^oF for 6.31-mm and 7.31-mm thick plates. The V_{50} data are given in Table 6.

Table 6. BALLISTIC PERFORMANCE AGAINST 7.62-mm M1943 BALL, 0^o OBLIQUITY

	V_{50} Velocity, ft/s		
	Room Temperature		-40^oF
Nom. Plate Thickness	Handbook Value	Measured	Measured
6.31 mm	2880	2857 & 2881*	2968
7.31 mm	2960 (extrap.)	2895 & 2909*	3007
7.31 mm XH	2990 (extrap.)	3091	---
9.71 mm	3200 (extrap.)	>3200	>3200

*Two plates were tested and two V_{50}s were determined.

The V_{50} values are close to the velocities obtained from the handbook,[7] with some values slightly above and some slightly below the nominal. A typical tested plate is shown in Figure 10. The penetration mode is by plugging for those projectiles with velocities exceeding V_{50}. The ballistic limit increases slightly at colder temperatures. No cracking was observed and all V_{50} values are well above the muzzle velocity of an AK47 or similar rifle, i.e., 2380 ft/s. The V_{50} of the 7.31-mm XH plate was higher than that for the regular hardness plate of the same thickness. This is not surprising since many past studies have shown that ballistic penetration resistance of steel correlates most closely with hardness.[8] The 7.62-mm ball threat would not penetrate the 9.71-mm thick plate at the velocities attainable and, thus, no valid V_{50} could be determined.

12.7-mm (.50 cal) API B32

At 0^o obliquity, the armor plates in question were not really thick enough to defeat a 12.7-mm API B32 projectile at reasonable velocities, i.e., standoff distances. Therefore, this threat was studied at 45^o obliquity, both to determine V_{50} values and to determine the integrity of the armor plate under ballistic impact, particularly at cold temperatures. The V_{50} values obtained at 45^o obliquity are summarized in Table 7.

Table 7. BALLISTIC PERFORMANCE AGAINST 12.7-mm API B32, 45^o OBLIQUITY

	V_{50} Velocity, ft/s		Single Shots, ft/s
	Room Temperature		-40^oF
Nom. Plate Thickness	Handbook Value	Measured	Measured
6.31 mm	2010	1886	1794,* 1783*
7.31 mm	2190	2176	2074,* 2063*
7.31 mm XH	2250	2255	2202,* 2195*
9.71 mm	2600	2528	2463,* 2507*

*No penetration

7. MASCIANICA, F. S. *Ballistic Technology of Lightweight Armor - 1981 (U).* U.S. Army Materials Technology Laboratory, MTL 81-20, May 1981, Confidential Report.
8. MENGANELLO, S. J., and ABBOT, K. H. *Metallurgical Factors Affecting the Ballistic Behavior of Steel Targets.* J. Materials, v. 7, no. 1, 1972, p. 231-239.

At -40°F single shots were fired at velocities just below the room temperature V_{50} to determine if any of the plates exhibited a propensity to crack at low temperatures. No penetration occurred for any of the shots. No cracking was observed under any conditions for the 12.7-mm (.50 cal) API B32 threat.

20-mm Proof Round

The four high hard armor plates were all tested with the 20-mm 70 g proof round at 0° obliquity at both room temperature and at -40°F. The intent of ballistic testing with this round was to determine the propensity (if any) of the armor plates to crack under ballistic shock loading conditions. The results are summarized in Table 8.

Table 8. BALLISTIC PERFORMANCE AGAINST 20-mm 70 g PROOF ROUND, 0° OBLIQUITY

	V_{50} Velocity, ft/s		Single Shots, ft/s
	Room Temperature		-40°F
Plate Thickness	Plate Hardness	Measured	Measured
6.31 mm	48 HRC	1751	1598*
7.31 mm	50 HRC	1919, Cracked	1691,* 1779* 1776, Cracked 1834, Shattered
7.31 mm XH	51 HRC	1818, Cracked	1774* 1761, 1815, Shattered 2290, Complete + Cracked
9.71 mm	48 HRC	1925	1840,* 1814*

*No penetration

While V_{50} values were obtained, the primary purpose was to obtain a measure of cracking/shattering resistance. Shattering is defined where the plate is broken into two or more pieces, while cracked plates exhibit cracks emanating from or adjacent to the projectile impact point. Both of the plates with a hardness of 48 HRC, i.e., 6.31 mm and 9.71 mm, did not exhibit any cracking tendency when tested at either room temperature or -40°F. However, both the 7.31-mm plates (the so-called normal and XH materials with 50 HRC and 51 HRC, respectively) cracked under the 20-mm proof round impact at both room temperature (72°F) and at -40°F. Examples of cracked and shattered plates are shown in Figures 11a and 11b, respectively. Thus, in this case, ballistic behavior at room temperature is indicative of behavior at subzero temperatures, i.e., no drastic change occurs and, hence, room temperature testing can be used to indicate any cracking tendency. However, this may not be generally true for other armor plate, other thicknesses, other obliquities, or other projectiles.

Welding

A considerable amount of welding work was done in support of this program; welding procedures and repair procedures were evaluated, vehicle production welds and repair welds were examined, failed weldments and weld components were examined, and the high hard base metal weldability was evaluated. Details of this study will be found in an MTL technical report presently in process,[9] the results of which are summarized here.

9. MELVIN, T. G. *Welding Study of MIL-A-46100*. U.S. Army Materials Technology Laboratory, technical report in process.

An examination of DDGM vehicle production welding procedures revealed nothing unusual or outside of the standard industry practice for welding thin plate armor steel. Vehicle production weld quality appeared to be good, considering the difficulties that can be encountered when welding high hard plate. However, the hardness in the HAZ tended to exceed industry norms for a "good" weld.

Weldability testing at MTL showed the high hard plate to be highly susceptible to hydrogen-assisted cold cracking. The following conditions are necessary for this mechanism to operate:

- A susceptible microstructure; for example, untempered or first-stage tempered martensite,
- A critical amount of diffusible hydrogen, and
- High tensile stresses (residual in the plate and/or introduced during fabrication).

Removal of any one of the conditions will be a deterrent to this type of cracking. Cold cracking occurring in high hard plate weldments fabricated in the MTL weld lab appeared as underbead cracks that were not always visible on the plate surface. The crack would initiate at the root of the weld and propagate in the base metal HAZ near the fusion line. Further propagation would likely occur at a later date if increased stresses were introduced.

An examination of failed welded components from fielded vehicles indicated that they probably also failed due to hydrogen-assisted cold cracking. In addition, it is possible that these cracks were initially underbead cold cracks that were undetected during manufacture of the vehicle which then propagated into detectable size cracks when service stresses were applied.

Failed field repair welds also appeared to be caused by hydrogen-assisted cold cracking. Field repair welding procedures and techniques being employed by repair welders were found to be inadequate. It was agreed that a detailed USMC LAV weld repair handbook would be beneficial for providing proper field weld repair guidance to reduce the cracking problem.[10]

Future vehicle production using MIL-A-46100 for welded structural applications is not recommended because of its high susceptibility to cracking. If, however, this material is used recommendations to the manufacturer include implementation of increased control over the welding process, procedures, and consumables with the aim of reducing/eliminating the conditions favoring hydrogen-assisted cracking. Because this material will always have a susceptible microstructure, residual (tensile) stresses should be reduced and, more importantly, the amount of diffusible hydrogen must be minimized.

Steel

The high hard armor used in the 758 LAVs built for the USMC was purchased to MIL-A-46100, mostly Revision C. The experience at DDGM with this steel led to the development of Canadian Material Specification CMS-18 (CMS-18). Revision A of this specification has recently been issued. CMS-18 is a restricted version of MIL-A-46100 so that all steel that meets the requirements of CMS-18 will also meet those of MIL-A-46100. The main restrictions are for lower carbon contents of the steel, a lower hardness range, and higher Charpy V-notch impact toughnesses. Because of these and other restrictions steel made to CMS-18 will be more expensive than that made to MIL-A-46100 although related fabrication and repair costs should be decreased.

10. MELVIN, T. G. *Second and Third Echelon Welder Repair Handbook for the USMC Light Armored Vehicle (LAV)*. U.S. Army Materials Technology Laboratory, MTL SP 92-1, January 1992.

Steel Producers

There was a long history of steel procurement for the USMC vehicles with several steel producers and heat treaters involved. For the final production period Lukens Steel Company was the principal supplier. As is the case with any material, there are learning curves associated with producing and welding this material. Apparently, as experience was gained at Lukens and DDGM with light gage high hard steels, the cracking problems decreased markedly.

Lukens Steel Company

At present, Lukens is the only North American producer that is supplying hard steel armor plate. Lukens has both continuous (strand) casting and ingot casting capabilities using a 165-ton electric furnace. Continuous casting is a considerably cheaper process because of the higher product yields and is being increasingly used worldwide. It is by far the dominant process today. In 1987, 59% of raw steel output in the USA was continuously cast compared with 7% in 1973 and 20% in 1980. Developed countries have even higher percentages with 80% in the European Economic Community and 93% in Japan continuously cast. A full 75% of all steel in the western world was continuously cast in 1987 and the numbers are even higher today. Lukens' caster produces slabs 9" thick x 96" wide. For other processing equipment improvements, Lukens has recently installed a ladle degassing unit that will improve quality and decrease steelmaking costs. This tank degasser will also ensure low hydrogen levels in the steel.

After some cross-rolling of the continuously cast (or ingot) slab, the steel is hot rolled to final gage on plate mills. Heat treatment is accomplished in-house on a continuous horizontal roller quench line. After austenitizing for about 20 minutes, the steel is progressively spray-water quenched from both sides while slowly passing through rolls to maintain flatness. The quenched plate continues down the line and into the tempering furnace.

Lukens has now accepted CMS-18A and has been qualified by DDGM to provide steel to this specification. Lukens also supplies MIL-A-46100 steel for other applications such as the M1 tank program, and it would be very desirable from their viewpoint to be able to use the product from one heat for both LAV and M1 plate.

Creusot-Marrel

This French company was the first to accept CMS-18 and supplied high hard plates for certain LAV components for the Canadian buy, e.g., hatch covers, etc. Creusot-Marrel casts all of their steel into relatively small ingots. After austenitizing, the plates are clamped in a platen system and quenched into a vertical oil bath that reportedly minimizes residual stress and plate distortion. Both the quenching and tempering are batch operations. The batch tempering of a stack of plates may cause problems in the uniformity of the time each plate "sees" the required tempering temperature. A D650 (Exploitation of Foreign Materiel) program is presently underway at MTL to more fully define the benefits (if any) of the French steel. Creusot-Marrel also has a laser cutting system that as far as is known is unparalleled in the United States. This system can be used to cut plates to any shape with excellent edges.

Since the steel is made in smaller heats (compared with Lukens), is ingot cast, and undergoes some batch processing, it probably will be more expensive.

Carbon Content

The ASTM requirement for chemical composition of steels with a ladle analysis of up to 0.30 wt% carbon allows ± 0.02 wt% carbon in a product analysis. However, CMS-18, CMS-18A, and MIL-A-46100 all specify product analysis. To meet all the product mechanical and ballistic property requirements of CMS-18 the steel producer realistically must make the melt (ladle analyses) with 0.29 ± 0.01 wt% C. If the carbon is any lower, the hardness and ballistics will not be met, and if it is any higher toughness will be difficult to attain (and weldability impaired). This is a very narrow carbon range and only a few years ago could not be consistently met. It is only with the advent of new ladle metallurgy processing that steels with this narrow carbon range can be practically produced.

Tempering

High hard armor is tempered between 350°F and 450°F. The minimum temperature of 350°F was introduced into MIL-A-46100 in Revision C (13 June 1983) after some plates that were tempered at much lower temperatures experienced cracking problems. Above ~450°F, alloy steels exhibit temper embrittlement with a lowering of toughness values. Therefore, metallurgically, this is a good range.

SUMMARY AND CONCLUSIONS

Cracking

It is concluded that much of the cracking occurring in LAVs that initiated at free cut edges may be attributed to environmentally-assisted cracking where there was some untempered martensite present. Cracks that initiated at welds were attributed to a number of possible causes: stress-corrosion cracking, underbead cold cracks undetected during vehicle manufacture that propagated to detectable sizes, hydrogen-assisted cold cracking due to improper field repair techniques, and cracks resulting from extremely harsh vehicle use.

Mechanical Properties

The tensile properties, Charpy V-notch impact toughness and hardness of four plates of varying thickness of MIL-A-46100 were measured at room temperature and at -40°F (-40°C). The hardnesses of the four plates were 48, 48, 50, and 51 HRC. The mechanical properties measured were all typical of an alloy steel of about 50 HRC. At room temperature, tensile strengths were about 250 ksi to 260 ksi, yield strengths 200 ksi to 210 ksi (0.2% offset), 10% elongation, and 40% to 50% reduction of area. At -40°F both strength and ductility were similar to the values obtained at room temperature. The Charpy impact values decreased slightly as the test temperature was lowered from the room temperature of 72°F to -40°F. All values exceeded the requirements of MIL-A-46100, except the 9.71-mm plate had slightly lower than specified Charpy impact energy at -40°F. Steels of the same hardness are used in many critical structural applications. For example, highly stressed aircraft landing gear components are almost invariably made of 300M, a steel of somewhat higher hardness and similar ductility and toughness.

Ballistic Properties

The ballistic properties of the same four plates were studied with 7.62-mm M1943 ball, 12.7-mm (.50 cal) API B32 and 20-mm 70 g proof round threats. These ballistic properties were measured from room temperature (72°F) to -40°F and at the various target obliquities up to 45°.

The V_{50} values were consistent with handbook values[7] in those cases where it was possible to match plate thickness, threat, and obliquity. One of the objectives of the ballistic testing was to determine the propensity of this steel to crack at low temperatures under heavy loading. The blunt-nosed proof round was used for this purpose. The only cracking observed occurred for the two plates having higher hardnesses. Both plates with a hardness of 48 HRC did not exhibit any cracking under any of the conditions tested.

RECOMMENDATIONS

Since plate edge cutting is so important it is recommended that laser cutting be considered. This procedure would reduce the thickness of the HAZ of cutting to a level that would obviate edge grinding.

Underwater plasma cutting of high hardness armor steel is not recommended, but if it remains the standard procedure, then edge grinding should be done immediately (less than one hour) after cutting. Delays could cause cracks to initiate and grow to a size that would not be subsequently removable. It is imperative that careful grinding to remove any fresh, brittle, untempered martensite must be accomplished without introducing excessive heat.

The ballistic study has shown that steel with higher hardness (and carbon content) is more prone to cracking. The Charpy V-notch impact toughness is also improved at lower hardnesses. Thus, this study has confirmed experience at DDGM that higher hardness (i.e., higher carbon steel) should be avoided. It is recommended that the Canadian Material Specification, CMS-18, be employed for future purchases of high hard armor steel for the LAV. The lower carbon content and restricted hardness range specified in CMS-18 is a step in the right direction, although it is likely that further modifications will occur in the future as experience is gained. Because of this tighter specification, initial cost of the steel will be higher, but lifetime vehicle costs should be lower.

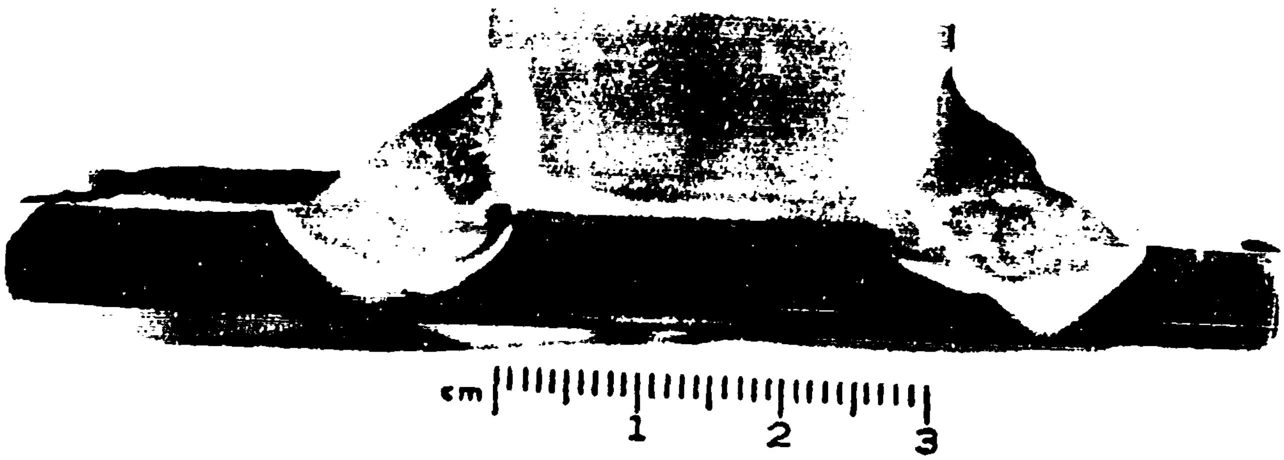
MIL-A-46100 was originally developed as an appliqué armor and was never intended to be used in a welded structural application. It should be stressed that as long as this or other stage-one tempered material is used on the LAV, weldment cracking will never be completely eliminated. However, recommendations can be made to help minimize the cracking problem. Additional welding process and consumable controls should be implemented for future vehicle production to further reduce diffusible hydrogen levels and residual stresses in the weld area. It should also be noted here that preheat should be considered for the welding of high hard plate; even if used only for moisture removal from the weld joint, preheat would be beneficial. Furthermore, it is recommended that austenitic stainless steel weld wire be investigated as austenitic welds are much less susceptible to hydrogen-related cracking. This is standard practice in Europe, i.e., a 0.42 wt% carbon armor steel on the German Leopard tank is welded with stainless steel wire. However, stainless steel filler metal has its own shortcomings and must be thoroughly investigated and tested prior to implementation.

ACKNOWLEDGMENTS

The authors wish to thank COL. Reed T. Bolick, LAV-PM, and Mr. Ben Nelsen, LAV-PMO, for their support and guidance during the performance of this study.

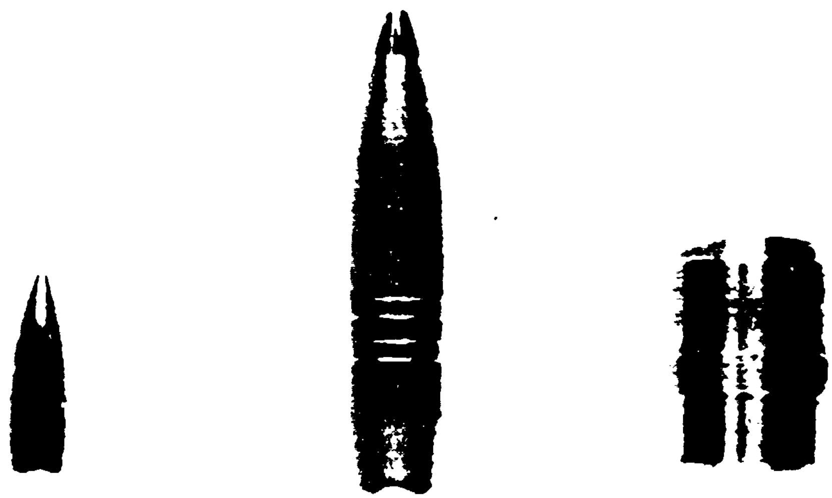
Individuals within MTL who have contributed significantly to this program include Mr. Gene DeLuca, Dr. George Bishop, and Messrs. Wayne Bethoney, Bill Crenshaw, Bob Pasternak, and Jim Catalano.

(a)



(b)

Figure 1. (a) Lift-eye, and (b) Weld cross section of DDGM test specimen no. 2.



Projectile →	Soviet 7.62-mm Ball, M1943 .30 cal	Soviet 12.7-mm API, B32 .50 cal	MTL 20-mm proof round .79 cal
Net Weight (grains)	123	746	1080
Core Weight (grains)	55	455	N/A
Core Type	Mild Steel	Hard Steel (65 HRC)	Mild Steel (AISI 1018)

Figure 2. Test projectiles used in this evaluation.

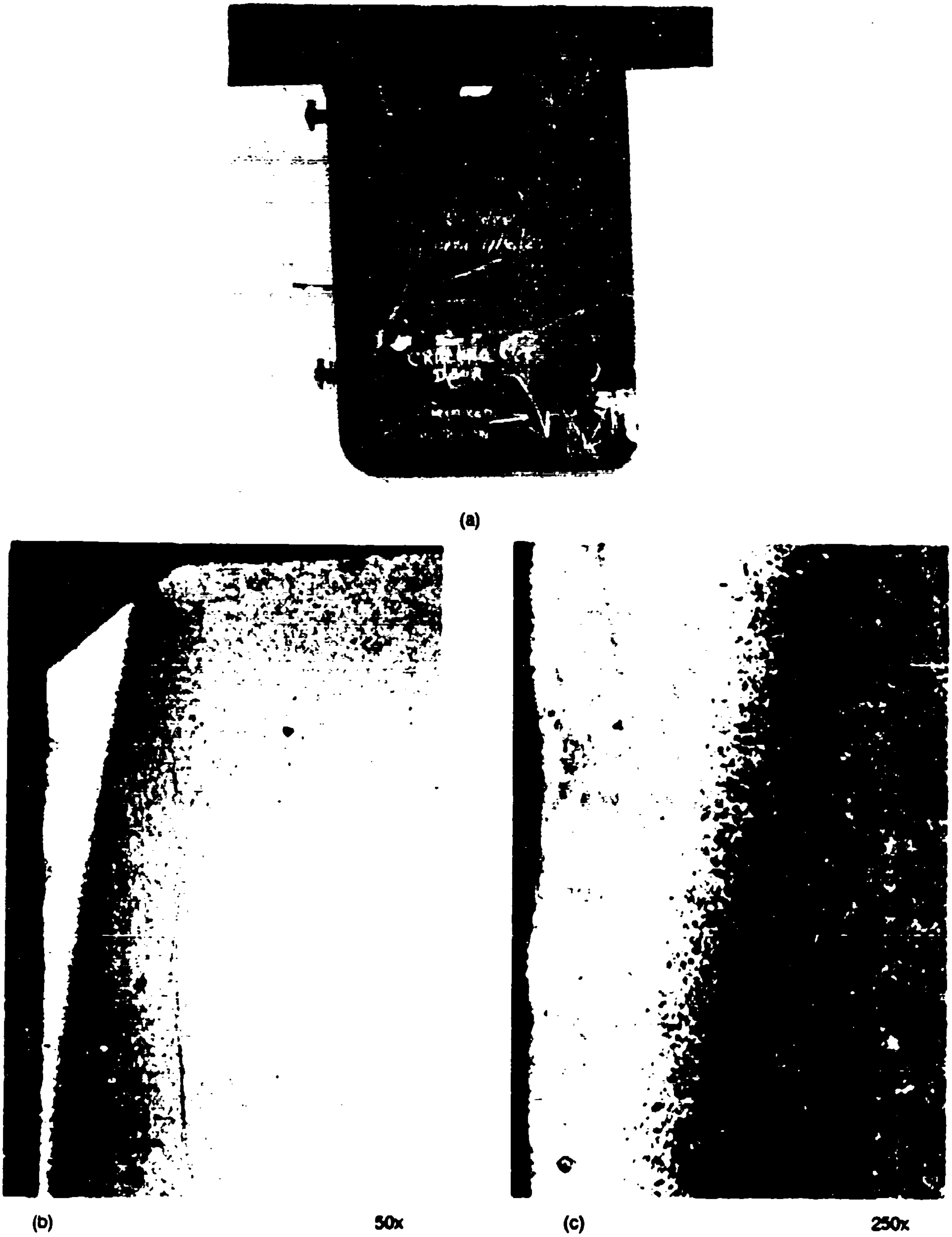


Figure 3. (a) Cracked rear door, (b) Optical micrograph of edge of cracked door, showing region of untempered martensite (light area), and (c) Higher magnification view of (b).

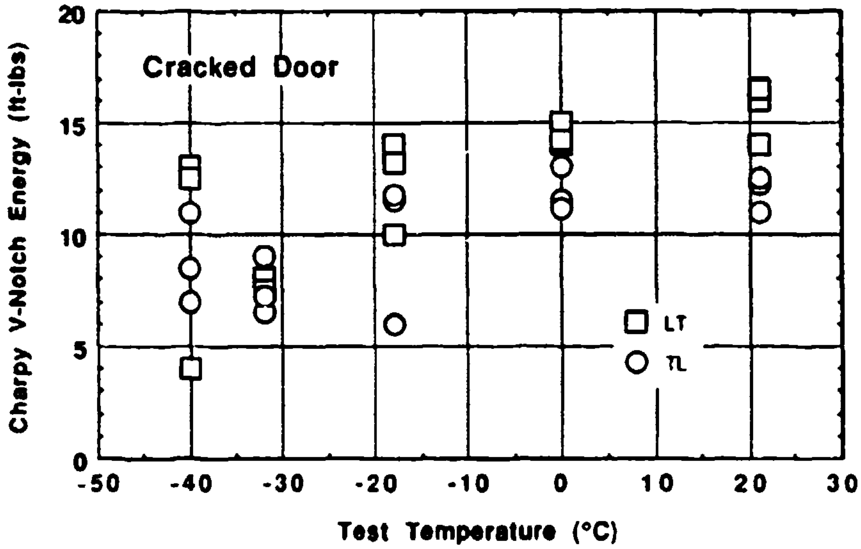


Figure 4. CVN energy (3/4-size specimens) versus test temperature; cracked door.

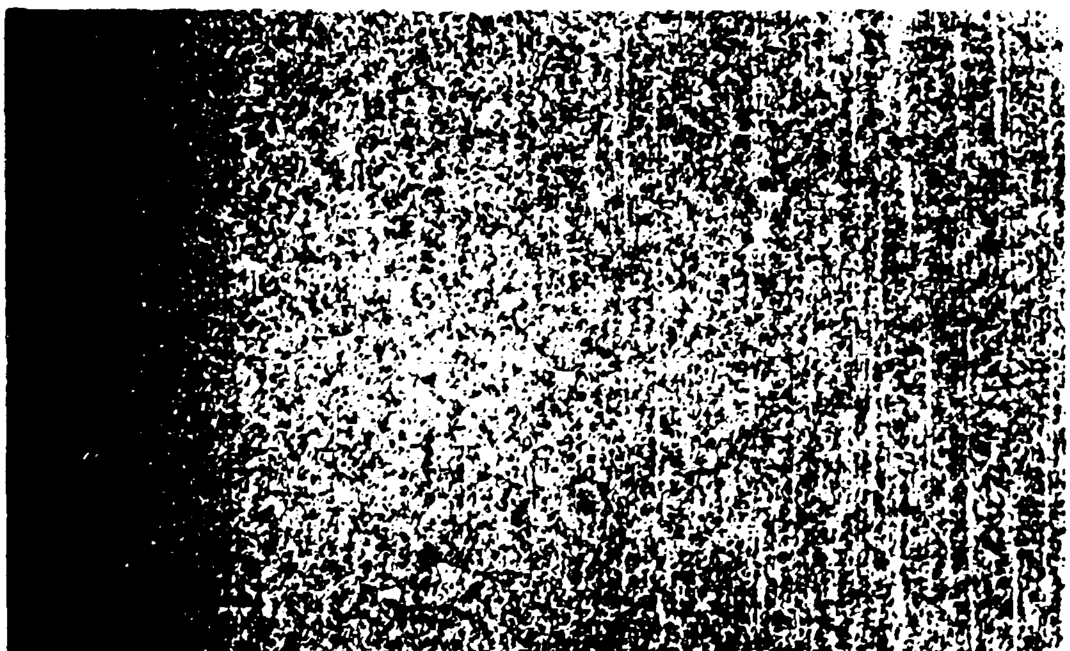
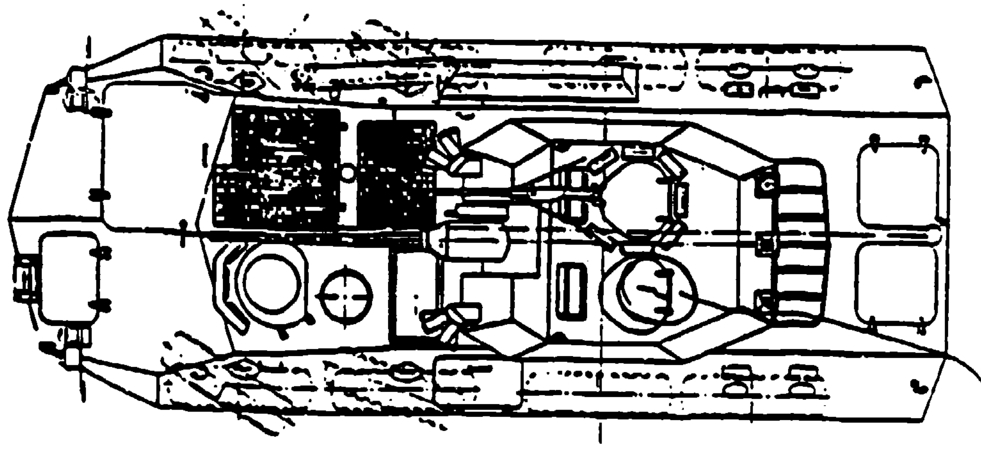


Figure 5. Optical micrograph of edge of cracked rear door showing decarburization and banding. Mag. 50X



MODEL 25 MC. AUTHOR A. KITTELBERGER.
DDGM S/N LAU. 612 REPORT DATE 07/15/87
USMC S/N 521765 HULL ☐
VEH MILES 128.9 HATCH ☒
VEH HOURS 15.8 DOOR ☐
VEH LOC'N ALBANY, GA.
UNIT USMC LB.

STORYBOARD

- CRACK LENGTH 8.00 INCHES.
- START/STOP POINT Crack started at the
- COMMENTS back edge of hatch and moved to the center of the plate.
  -Hatch was replaced by DDGM.

Figure 6. Field service report for cracked hatch.

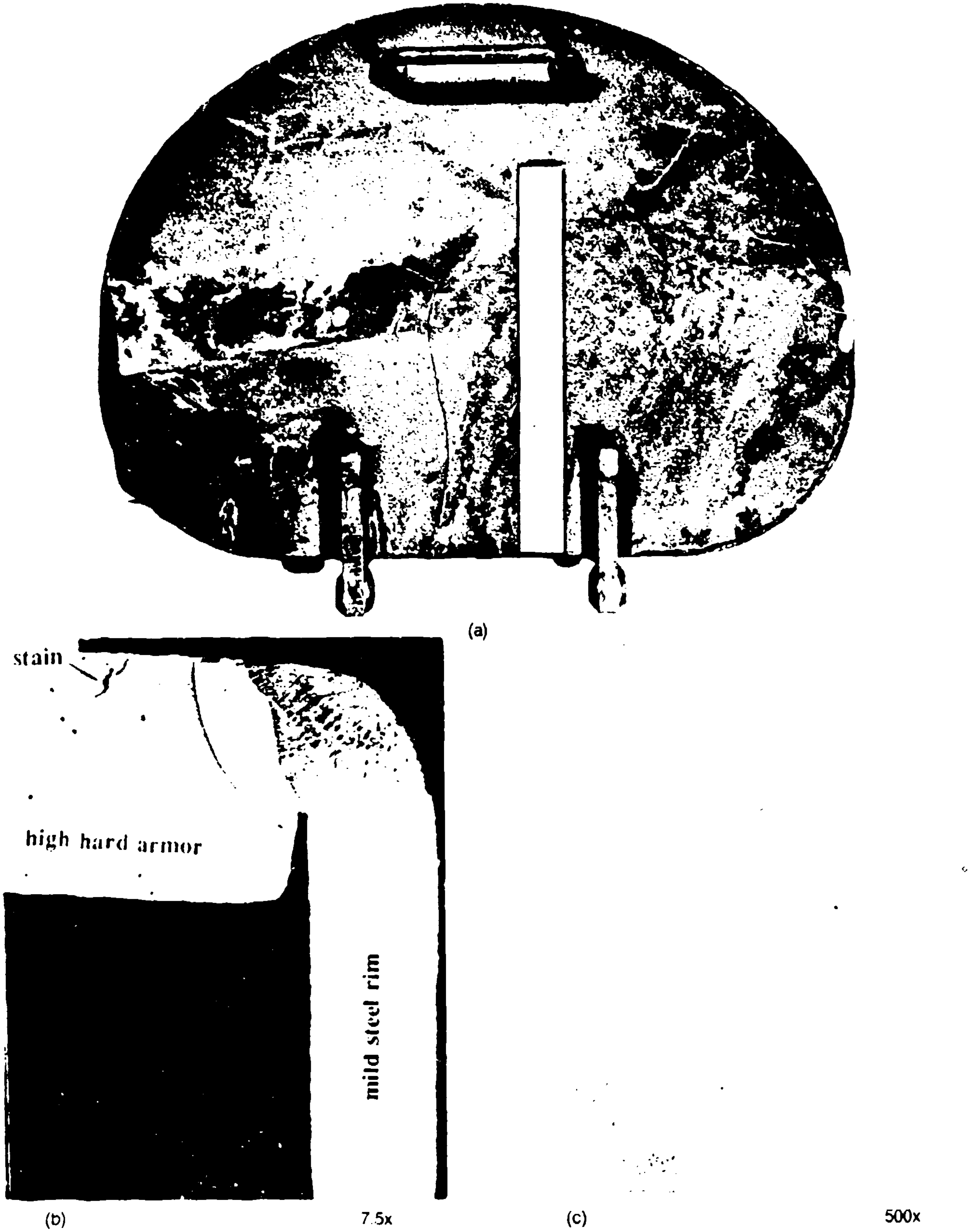


Figure 7 (a) Cracked turret hatch cover, (b) Macrograph of edge of cracked hatch cover, and (c) Optical micrograph of HAZ

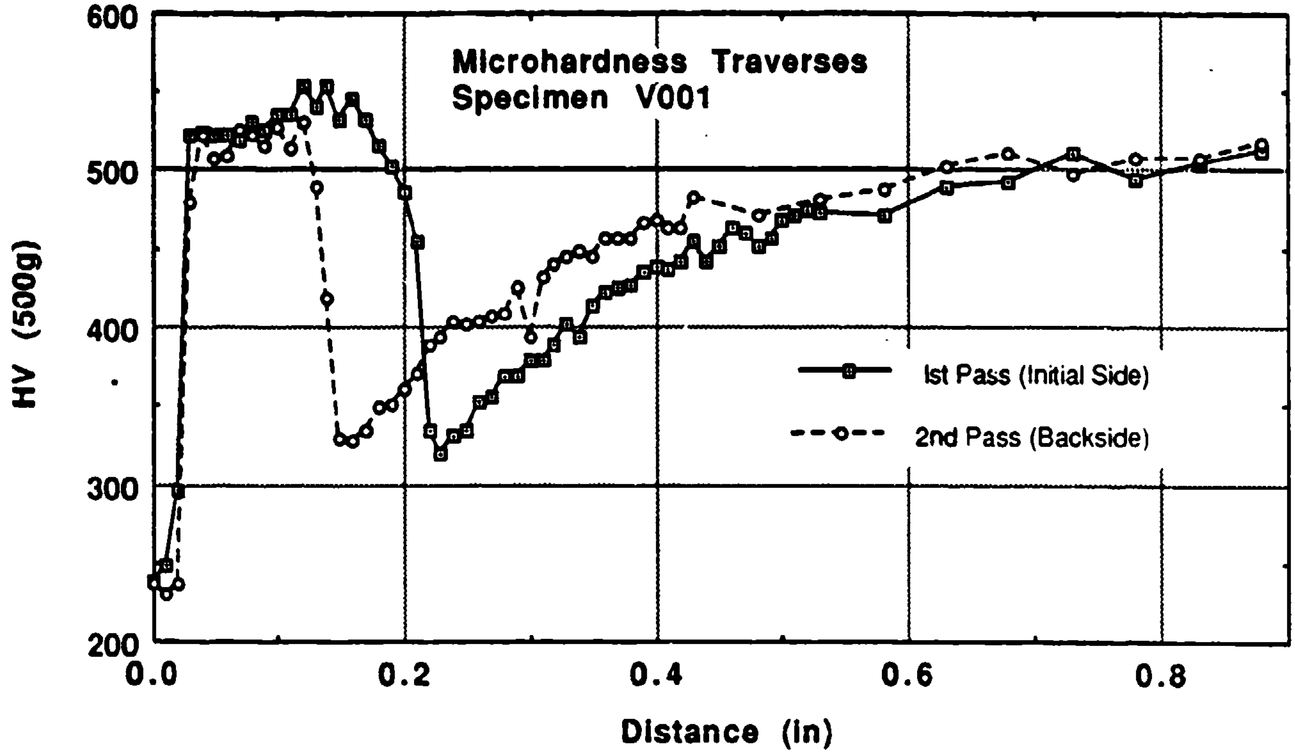


Figure 8. Microhardness tranverses across a weld from dropped LAV.

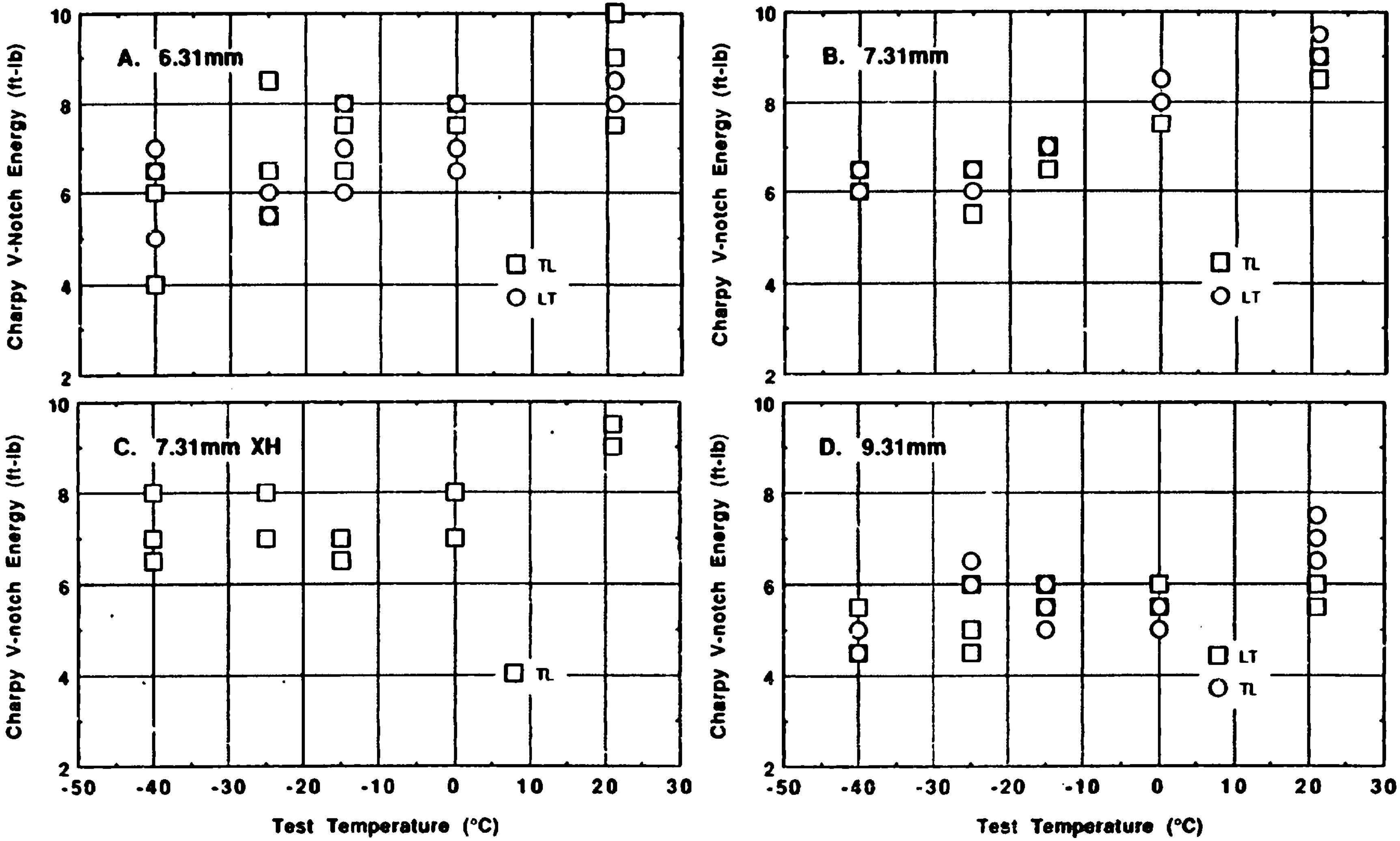


Figure 9. Charpy impact energy (1/2 size specimens) versus temperature for (a) 6.31-mm plate, (b) 7.31-mm plate, (c) 7.31-mm XH plate, and (d) 9.71-mm plate.

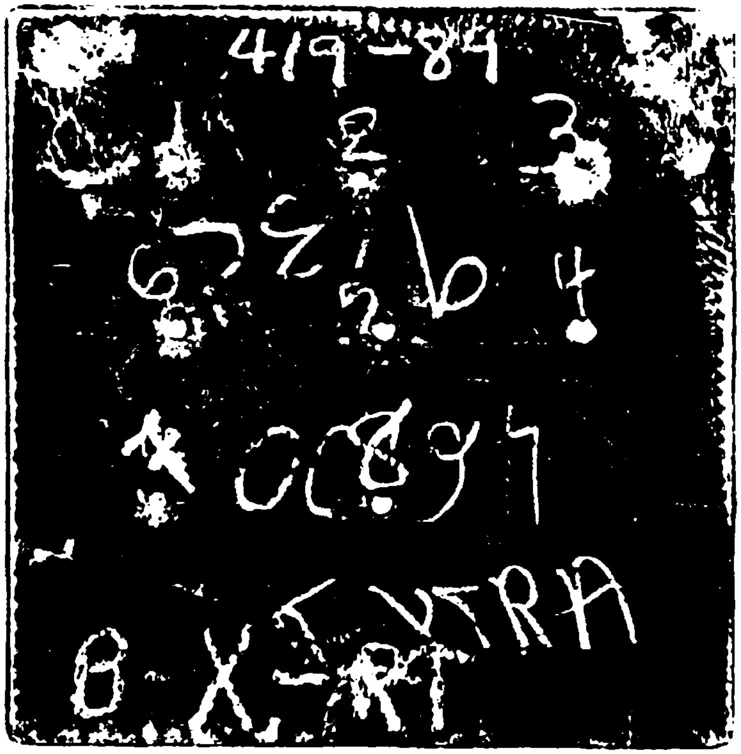
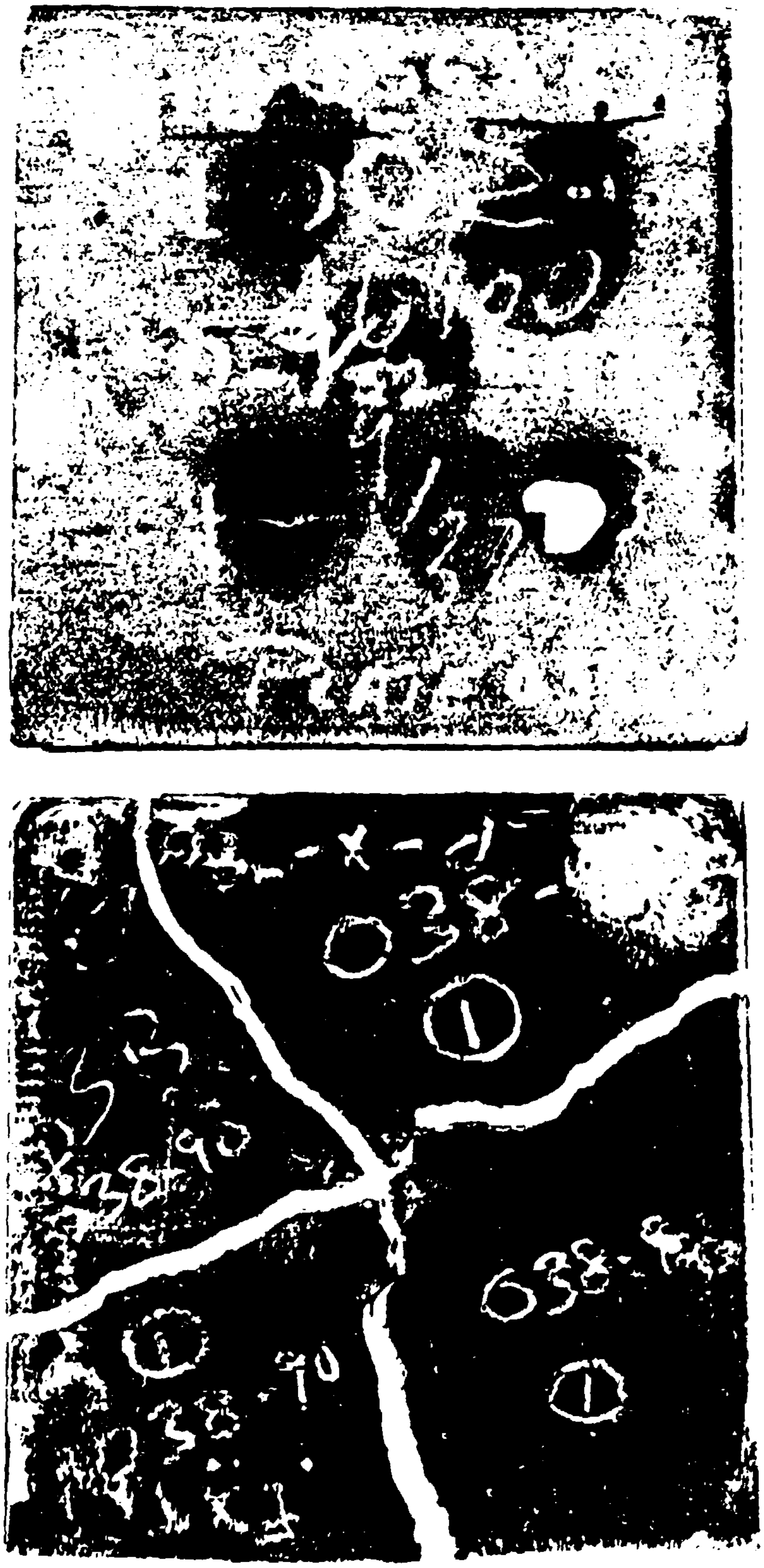


Figure 10. Photograph of 7.31-mm XH plate after ballistic testing against 7.62-mm M1943 ball at 0° Obliquity at room temperature, showing partial and full penetrations by plugging.



(a) Room Temperature

(b) -40°F

Figure 11. Photograph of 7.31-mm plate after ballistic testing against 20-mm proof round at 0° Obliquity, showing plate cracking and plate shattering.

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